A STUDY ON THE RELATIONSHIP BETWEEN ROCK STRENGTH, RQD, AND THE PRODUCTIVITY OF VIBRATORY RIPPER

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ABSTRACT: The primary objective of this research is to enhance the field applicability of excavator-mounted vibratory rippers by quantitatively estimating their productivity based on rock mass characteristics. Despite its practical importance, academic research on vibratory rippers remains limited, particularly studies that simultaneously account for the effects of rock strength and rock mass discontinuities. In this study, a productivity prediction model incorporating both uniaxial compressive strength (UCS) and rock quality designation (RQD) is proposed and validated through field tests. The field test results indicate that the vibratory ripper achieves approximately fourfold excavation efficiency of a hydraulic breaker, with its performance being most pronounced in highly jointed rock masses. Furthermore, the performance gap between the two types of equipment tends to narrow as rock strength increases. Although the generalizability of the proposed model may be constrained by the limited dataset size, this study contributes to improving the prediction accuracy of vibratory ripper productivity by jointly considering UCS and RQD. The findings are expected to provide a foundational basis for the future development of multivariate productivity prediction models.

1. INTRODUCTION

Rock excavation is a critical process that significantly impacts both the construction period and the economic feasibility of civil and construction projects. In general, conventional rock excavation has been primarily carried out using blasting methods. However, in recent years, the application of blasting has become increasingly restricted in urban areas due to concerns regarding noise, vibration, and safety. Consequently, the utilization of mechanical excavation methods has been expanding, and the use of ripper equipment has also been on the rise (Milanović et al., 2023).

A ripper is an excavation tool designed to fragment rock mechanically. Its fracturing mechanism involves penetrating the rock with a ripper tip to induce localized stress concentrations, which cause tensile cracks to propagate and separate along joints or weak zones. Ripper equipment is generally classified into bulldozer-mounted and excavator-mounted types. Bulldozer-mounted rippers, which have ripper tips attached to the rear of a bulldozer, are advantageous for projects requiring wide working widths and continuous excavation. In contrast, excavator-mounted rippers are attached to the boom and arm of an excavator as an attachment, enabling relatively precise excavation in confined spaces.

Recently, vibratory rippers—which separate rock by inducing repetitive stress through high-frequency vibrations generated by eccentric gears—have been developed and popularized, leading to an increase in their field application. However, previous research providing quantitative evaluations of vibratory ripper performance, particularly studies that simultaneously consider rock strength and rock mass discontinuities, remains very limited. Therefore, this study aims to classify and analyze the excavation performance of vibratory rippers according to specific RQD levels. This is achieved by utilizing maximum productivity data provided by manufacturers and empirical RQD-based models presented in existing literature.

2. RESEARCH METHODOLOGY

2.1 MANUFACTURER DATA OF EQUIPMENT

Technical data provided by equipment manufacturers specify the maximum productivity of vibratory rippers and hydraulic breakers according to rock types and Uniaxial Compressive Strength (UCS). In this study, the maximum productivity data for vibratory rippers provided by the manufacturer were assumed to represent ideal joint conditions, specifically a Rock Quality Designation (RQD) of 10%.

Model training and evaluation were conducted based on these data. Given the limited dataset, the application of machine learning is expected to encounter challenges such as data bias and overfitting. Nevertheless, in this study, machine learning was utilized as an auxiliary tool to quantitatively represent the nonlinear decreasing trend between UCS and productivity. Prior to the detailed validation process, hold-out validation was performed using data representing extreme values to rapidly assess initial model performance. Subsequently, more rigorous evaluations were carried out using K-Fold cross-validation and Leave-One-Out Cross-Validation (LOOCV).

2.2 BACK-CALCULATION OF RQD

Previous studies have established a Net Breaking Rate (NBR) model to predict the hourly productivity of impact hammers based on rock strength and RQD (Bilgin et al., 1996; Ocak et al., 2010). Using this model as a basis, the corresponding RQD values for each UCS were back-calculated through the manufacturer's maximum productivity data. Through this process, productivity levels for RQD values of 10%, 25%, 50%, and 75% were estimated as follows:

$$\mathrm{NBR} = 4.24 \times \mathrm{Pi} \times (RMCI)^{-0.567} \quad (1)$$

$$\mathrm{RMCI} = \mathrm{UCS} \times \left(\frac{RQD}{100}\right)^{\frac{2}{3}} \quad (2)$$

NBR represents the net breaking rate of the impact hammer, and Pi denotes the product of the hydraulic oil flow rate and the operating pressure.

2.3 FIELD TEST DATA

Field tests were conducted in Incheon, South Korea, to compare and analyze the excavation performance of the vibratory ripper and the hydraulic breaker. To evaluate performance relative to varying rock strengths, tests were carried out at four distinct locations within the site. To ensure consistent experimental conditions, both attachments were operated using the same 50-ton class excavator. Furthermore, the excavation points for the two types of equipment were set within 10 meters of each other to ensure they were tested under nearly identical geological conditions.

Each test was conducted for a duration of 10 minutes, with the UCS across the test sites ranging from 10 MPa to 120 MPa. The excavation volume was determined using 3D laser scanning, where the net volume was calculated by registering the data captured before and after the excavation process. During the volume estimation, the accuracy of the data registration was verified through the Root Mean Square (RMS) error; a threshold of 3 cm or less was used to confirm successful alignment and data integrity.

Table 1: Specifications of Equipment

Equipment Type	Applicable excavator (ton)	Operating pressure (bar)	Operating flow rate (L/min)	Impact frequency (bpm)	Operating speed (rpm)
Vibratory ripper	50	250	320	-	1600
Hydraulic breaker	50	250	240	550	-

3. RESULTS

3.1 CROSS VALIDATION

In the performance assessment conducted via hold-out validation, Multi-Layer Perceptron (MLP), Random Forest (RF), and Gamma Regression demonstrated relatively high performance. However, MLP and RF were deemed unsuitable for the current study due to their high sensitivity to dataset size and were consequently excluded from further analysis. Subsequently, cross-validation was performed using K-Fold and Leave-One-Out Cross-Validation (LOOCV) methods. While cross-validation is typically employed to evaluate a model's generalizability and prevent overfitting, in this research, it served as a fundamental assessment to verify the consistent explanatory power of the model within a data-constrained environment.

The cross-validation results revealed that Gamma Regression achieved a coefficient of determination (R^2

) of approximately 0.946 for LOOCV and an average R^2 of 0.881 for K-Fold. Performance fluctuations observed in certain K-Fold subsets were attributed to statistical variability resulting from the limited number of data points available for training and testing.

3.2 RQD ESTIMATION BASED ON BILGIN ET AL. (1996)

Based on the trendline generated via the Gamma Regression model, the scaling ratios relative to the remaining RQD curves were identified. For each Uniaxial Compressive Strength (UCS) point, productivity ratios for RQD levels of 25%, 50%, and 75% were calculated using the RQD 10% curve as a baseline. Table 2 summarizes these ratios relative to the reference curve.

Table 2: Scaling Ratios and Exponential Slopes for Different RQD Conditions

RQD (%)	Productivity Ratio	Exponential Slope	Productivity Model
10	1.000	0.017	$P_{10} = 388.02 \cdot e{-0.017 \cdot UCS}$
25	0.707	0.017	$P_{25} = 274.43 \cdot e{-0.017 \cdot UCS}$
50	0.544	0.017	$P_{50} = 211.17 \cdot e{-0.017 \cdot UCS}$
75	0.4667	0.017	$P_{75} = 181.17 \cdot e{-0.017 \cdot UCS}$

It should be noted, however, that the values calculated through this method are theoretical and do not account for inherent physical and mechanical limitations. Therefore, practical constraints such as machine output and field efficiency must be considered. In high-strength rock conditions exceeding 150 MPa, productivity was deemed to reach a lower bound where no further significant decrease occurs due to equipment-specific and physical limits. Conversely, for rock strengths below 10 MPa, any further reduction in strength is expected to yield negligible increases in productivity, as the process becomes limited by the equipment's operating speed and mechanical capacity. Consequently, it is necessary to establish the range between 10 MPa and 150 MPa as the effective interval for productivity variation.

3.3 FIELD TEST RESULTS

Visual inspection of joint conditions at the test sites indicated that Site A exhibited the most developed joint structure, whereas Site C showed the least degree of jointing. The field test results demonstrated that the vibratory ripper achieved a maximum hourly excavation efficiency approximately four times higher than that of the hydraulic breaker. In addition, consistent with the data provided by the manufacturer, a clear trend was observed in which the performance gap between the two types of equipment decreased as rock strength increased.

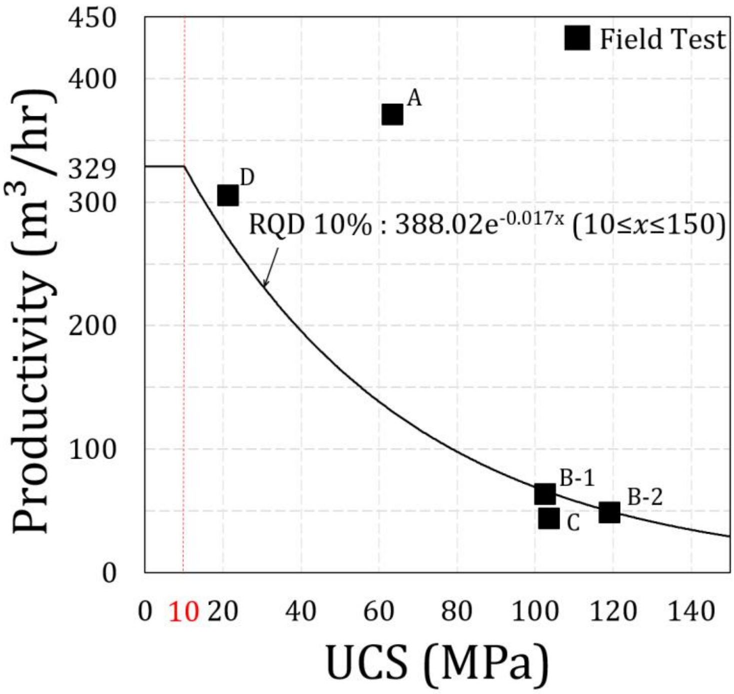

Figure 1: Comparison between the Gamma regression based productivity curve for RQD = 10% and the field test results of the vibratory ripper.

Figure 1 presents a comparison between the Gamma regression–based productivity curve for an RQD of 10% and the corresponding field test results. In particular, the productivity of the vibratory ripper was markedly higher at Site A, which is interpreted as being due to the easier detachment of relatively large rock blocks during excavation. Overall, the field test results exhibit a trend that is closely aligned with the productivity curve predicted for the RQD 10% condition.

4. CONCLUSION

In this study, a productivity prediction model incorporating both Uniaxial Compressive Strength (UCS) and Rock Quality Designation (RQD) was proposed and validated through field tests to evaluate the excavation performance of vibratory rippers. The key conclusions derived from this research are as follows.

First, the decreasing trend of vibratory ripper productivity relative to increases in UCS was quantitatively modelled using a Gamma regression algorithm. The analysis demonstrated that the Gamma regression model possesses high explanatory power in representing this relationship.

Second, a productivity model for various RQD levels was established based on the empirical equations of Bilgin et al. (1996). The results confirmed that the excavation efficiency of the vibratory ripper increases significantly as joint development becomes more prominent. By defining a valid productivity variation interval that accounts for mechanical limitations, this study sought to minimize potential errors during practical field applications.

Third, field tests conducted in Incheon verified that the vibratory ripper exhibited up to approximately four times the efficiency of conventional hydraulic breakers. Furthermore, it was observed that the performance gap between the two types of equipment tends to narrow as rock strength increases.

This research is significant in that it provides a fundamental framework for precise productivity prediction by integrating both UCS and RQD. However, there remains a need to enhance model reliability and expand into multivariate predictive models by incorporating larger datasets and additional influential factors. To achieve this, continuous efforts to secure more field productivity data and implement systematic data management for vibratory rippers are considered essential.

5. ACKNOWLEDGEMENTS

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